[0085] The highest performance is obtained with horizontal upward orientation of the chip. The authors give a mathematical expression relating q_{CHF} to inclination angle.

[0086] The authors give quantitative measures of increase in q_{CHF} due to channel wall surface roughness in microchip applications as 32.5% and 48%. These results were obtained for average values of surface roughness ϵ of 1.1, 18.7 and 309.3 nm, respectively, as compared to a 1.1 nm surface roughness base case. Furthermore, they generated boiling curves for various values of equivalent porous cavity mouth diameter and porous and engineer pin-fin designs. The enhancement in heat flux at a given wall superheat temperature can be compared to the smoothest surface, Chip S (ϵ=1.1 nm), and predictions for convective boiling which assumes a perfectly smooth surface (ϵ=0).

[0087] Ramaswamy et al. (2002) describe a study of surface-enhanced boiling in a microchannel using wafer dicing and wet etching was used to fabricate a net of interconnected microchannels on a 10 mm×10 mm piece of silicon wafer. The resultant structure has pores that communicate the interior of microchannels to the liquid pool. The pore diameter was varied in a range 0.12-0.20 mm and the pore pitch in 0.7-1.4 mm. The data were collected maintaining the system pressure at one atmosphere and increasing the wall superheat up to 12 K. A summary of their findings is as follows:

[0088] For low to intermediate wall superheat values (4-12° C.), the boiling took place in the isolated bubble regime. With an increase in the wall superheat, coalescence begins to occur, leading eventually to formation of large bubbles. The coalescence phenomenon was controlled to some extent by the pore pitch.

[0089] The average bubble departure diameter increased with an increase in the pore size (for same wall superheat). They report that the effect of pore pitch was very small. For a certain pore size, the bubble departure/detachment diameter increased with an increase in the wall superheat.

[0090] The frequency of bubble generation increased marginally with an increase in the wall superheat. At intermediate wall superheats (approximately 12° C.), the frequency showed a decreasing trend. Furthermore, the frequency reduced with an increase in the pore pitch and pore diameter.

[0091] The authors report that nucleation site density increased with an increase in the wall superheat (for all structures). A larger pitch resulted in fewer bubbles because of fewer pores. The pore size had negligible effect except for one structure where the number of bubbles increased. They maintain that the nucleation site density is a function of the volume evaporated inside the tunnels and the average departure diameter of the bubbles, and that with a change in the pore size, interplay of these two parameters leads to variability in the nucleation site density.

[0092] Wall Superheat

[0093] Small hydraulic diameter leads to low Reynolds numbers in the laminar regime, typically in the range 100-1000. In such low Reynolds number flows, nucleate boiling is generally required if good heat transfer characteristics in a two-phase microchannel application is to be achieved. However, the high degree of wall superheat oftentimes required to initiate nucleation in microchannels leads to "overshoot" or overly rapid evaporation which in turn can lead to bubble coalescence, slug flow, and various regimes of flow instability. One means of controlling boiling overshoot is to maintain the wall superheat temperature $\Delta T_{sat} = T_{wall} - T_{sat}$ (sometimes denoted as ΔT_{sup}) to as low a value as possible for nucleate boiling.

[0094] Kandlikar (2004) discussed flow boiling in a channel from the subcooled liquid entry at the inlet to a liquid-vapor mixture flow at the channel outlet. As the liquid flows through a microchannel, nucleation occurs over cavities that fall within a certain size range under a given set of flow conditions. Assuming that cavities of all sizes are present on the channel wall surface, he proposes that the wall superheat necessary for nucleation may be expressed based the equations developed by Hsu and Graham (1961) and Sato and Matsumura (1964) and the assumption that subcooled temperature difference is set identically to zero:

$$\Delta T_{sat,ONB} = \frac{8\sigma T_{sat} v_{fg} C}{D_h h_{fg}} \tag{16}$$

[0095] For channels larger than 1 mm, the above expression predicts that the wall superheat is quite small, but as the channel size becomes smaller, larger superheat values are required to initiate nucleation. For example, water in a 200-micron channel requires a wall superheat of 2° C. before nucleation can begin.

[0096] In the case of channels with hydraulic diameter less than 50 microns, the wall superheat requirement may exceed 10° C. with water, and above 2-3° C. for refrigerants. Flow boiling in channels smaller than 10 microns will pose significant challenges to achieve nucleate boiling.

[0097] When the wall superheat exceeds the temperature required to nucleate cavities present on the channel walls, nucleate boiling is initiated in a microchannel. Absence of nucleation sites of appropriate sizes may delay nucleation. Other factors such as sharp corners, fluid oscillations, and dissolved gases affect the nucleation behavior. The necessary wall superheat is estimated to be 2-10° C. for channels smaller than 50-100 micron hydraulic diameter with R-134a and water, respectively, at atmospheric pressure conditions.

[0098] One important factor to consider for all the wall superheat estimates using the above equation is that this expression is based on conventional channel boiling heat transfer correlations. The references for this expression predate all the literature on studies of boiling phenomena in microchannels by many years and therefore may not be applicable to microchannel wall superheat predictions.

[0099] Peng et al. (1997) report results that give larger values for wall superheat temperature at the same hydraulic diameter, such as illustrated in **FIG. 3**. They maintain that nucleate boiling in microchannels is much more difficult to achieve than in conventional size channels although they also hypothesize that the fluid is in a highly non-equilibrium state with an exceptional capacity to absorb and transport thermal energy.